Exhibit C

Prov. #1

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Preliminary specifications for electronic-tuning components

by

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Abstract

This note provides preliminary estimates of the required ratings and parameters of electronic-tuning components for an electronically tuned class-E power amplifier.

Indexing Terms

Amplifier, power, class-E
Amplifier, power, output filter
Inductor, permeability-tuned
Capacitor, voltage-variable

1. INTRODUCTION

The objective of this contract is to develop high-power electronic-tuning components, including:

- Semiconductor capacitor,
- Inductor, and
- Ceramic capacitor.

Toward the end of the contract (Tasks F1 and F3), the use of these components will be demonstrated. The application of greatest interest (selected at the kick-off meeting held at GMRR on November 30, 1998) is an electronically tunable high-efficiency power amplifier (PA). Harmonic content of the output is not of great concern, and low to medium power is sufficient for the present purposes.

The simplified circuit of a class-E PA with both tunable capacitors and inductors is shown in Figure 1. Capacitor C3 provides the variable drain-shunt susceptance. Inductors L2 and L3 and capacitor C5 form a variable-frequency T filter which (via L2) provides the inductive load reactance. Transformer T1 reduces the 50-Ω load impedance so that smaller breakdown voltages are required for Q1, C3, and C5. The amplifier topology shown in Figure 1 and tuning techniques are adapted from GMRR IR&D work [RN98-10]. Operation in the range of 10 to 30 MHz will result in reasonably sized components and freedom from undue concern over packaging and parasitics.

The purpose of this note is to provide preliminary estimates of the required ratings and parameters of the electronic-tuning components.

2. PA-LOAD IMPEDANCE

In the absence of a detailed nonlinear simulation of the class-E PA with the electronically tunable capacitor, it seems prudent to assume that $v_{D\max} = 4V_{DD}$. Typical LDMOS devices have breakdown voltages no higher than 60 V. Conventional RF-power MOSFETs intended for operation from a 50-V supply have breakdown voltages of 120 V. This suggests supply voltages of 15 or 30 V.

The resultant power outputs for ideal single-ended amplifiers with various drain-load resistances are given in Table 1. These results suggest using a 5.56-Ω load line, which corresponds to a 9:1 transformer. A real PA thus constructed should produce between 20 and 75 W, depending upon the supply voltage and ratings. The corresponding RF and peak voltages and currents are given in Table 2.

3. DRAIN-SHUNT CAPACITOR

The drain-voltage waveform in a class-E PA inherently has a high harmonic content and is isolated from the load by the T filter. Consequently, there is

no need to bias the drain-shunt capacitor so that the capacitance changes only a small amount over the range of the drain voltage. As a result, a minimum dc-bias voltage that is only slightly larger than V_{DD} is sufficient to ensure that the voltage on C3 does not become negative (and therefore cause diode conduction).

The maximum value of C3 occurs at the minimum value of v_{B1} ($\approx V_{DD}$). The capacitance of a two-terminal device is assumed to vary approximately as $v_{B1}^{1/2}$. Consequently, a 3:1 variation in capacitance requires a 9:1 variation in v_{B1}. Since the peak of the class-E waveform is $3V_{DD}$ above the supply voltage, the anticipated peak voltage on the tuning diode is $12V_{DD}$. The breakdown voltage should be 1 to 2 V_{DD} above the anticipated peak. Suggested values are given in Table 3.

The maximum value of C3 occurs at the minimum value of v_{B1}. For a low frequency of 10 MHz, obtaining a shunt susceptance of $0.1836/R$ requires 526 pF. The capacitor must be capable of handling the same peak current $i_{D\max}$ (Table 2) as the MOSFET.

4. INDUCTORS

Selection of $Q \approx 2.5$ in the T filter provides adequate harmonic suppression in the current application. For operation at 10 MHz, output inductor L3 must have a maximum reactance of $2.5R$, hence a maximum inductance of 0.22 μH. Optimum class-E operation requires a drain-load impedance of $R + j1.15R$. Input inductor L2 must similarly have a maximum reactance of $3.6R$, hence a maximum inductance of 0.265 μH. The peak RF current is equal to the RF-output current I_{om} in Table 1.

5. OUTPUT-TUNING CAPACITOR

The T filter (Chapter 2, [TR98-1]) can be implemented with either (a) both variable capacitor and inductors, or (b) only a variable capacitor. In either case, the maximum value of capacitor C5 is determined at the minimum frequency of operation by

$$\omega_0 C = 2Q / R_1 = \frac{2Q}{(Q^2 + 1) R_o} . \qquad (1)$$

For a minimum frequency of 10 MHz, C5 = 1974 pF.

The RF voltage and current that C5 must handle are related to those at

the output by

$$V_C = (1 + Q^2)^{1/2} V_o \approx Q V_o \quad . \tag{2}$$

and

$$I_C = V_C \omega C = \frac{2Q}{(Q^2 + 1)^{1/2}} \frac{V_o}{R_o} \approx 2I_o \quad . \tag{3}$$

If the inductors are variable, then Q is constant. If the inductors are fixed, then Q varies with frequency according to

$$Q = (\omega/\omega_l) Q_l \quad . \tag{4}$$

The resultant peak RF voltage and current are given in Table 4 for a 3:1 tuning range.

Since the present application permits a moderate amount of harmonic power to reach the output, it is sufficient for the dc bias v_{B2} on C5 to be just large enough to ensure that the voltage on C5 does not become negative at any point in the RF cycle. The range of bias voltages given in Table 4 is based upon a 20-V margin at the lowest bias voltage. The peak voltages on C5 are then calculated by adding the maximum RF voltage to the maximum bias voltage.

6. CONCLUSIONS

It is important to remember that the objective of this contract is to demonstrate the feasibility of components for high-power electronic tuning. It is better to produce a working prototype component with lower-than-desired ratings than to produce nonworking prototype with desired ratings. With this in mind, the following targets are suggested:

Inductor

- Maximum inductance 0.25 μH
- capable of 3-A RF.

Two-Terminal Capacitor

- 525 pF
- 500 - 600 V breakdown
- 4.4 A RF.

One such capacitor is used for C3; four in parallel are used for C5.

Three-Terminal Capacitor

- 525 pF
- 100 - 200 V breakdown
- 4.4 A RF.

One such capacitor is used for C3; four in parallel are used for C5. A breakdown voltage higher than the minimum is desirable as it will allow both fine (via control terminal) and coarse (via bias terminal) variation of capacitance.

R, Ω	P_o, W	
	V_{DD} = 15 V	30 V
12.5	10.4	41.5
6.25	20.8	83.1
5.56	23.3	93.4
3.125	41.5	166.2

Table 1. Power outputs for various load resistances and supply voltages.

PARAMETER	V_{DD} = 15 V	V_{DD} = 30 V
V_{om}, V	16.1	32.2
I_{om}, A	2.9	5.6
I_{dc}, A	1.55	3.1
v_{Dmax}, V	60	120
i_{Dmax}, A	4.4	8.9

Table 2. Amplifier parameters for R = 5.56 Ω.

PARAMETER	TYPE OF DEVICE	V_{DD} = 15	30 V
v_{B1}, V	2-terminal	15 - 230	30 - 410
	3-terminal	15	30
v_{max}, V	2-terminal	60 - 275	120 - 500
	3-terminal	75	150
i_C, A		4.4	8.9

Table 3. Voltage and current ranges for C3.

PARAMETER	CONDITION	V_{DD} = 15	30 V
V_{RF}, V	Tunable Ls	40.3	80.6
	Fixed Ls, 3:1 tuning	120.9	241.8
I_{RF}, A		5.6	11.2
v_{B2}, V	2-terminal, minimum	65	105
	maximum	585	945
v_{B2}	3-terminal	50	100
v_{max}, V	2-terminal, var Ls	625	1025
	fixed Ls	700	1186
v_{max}, V	3-terminal, var Ls	90	180
	fixed Ls	240	480

Table 4. Voltages and current for tuning capacitor C5.

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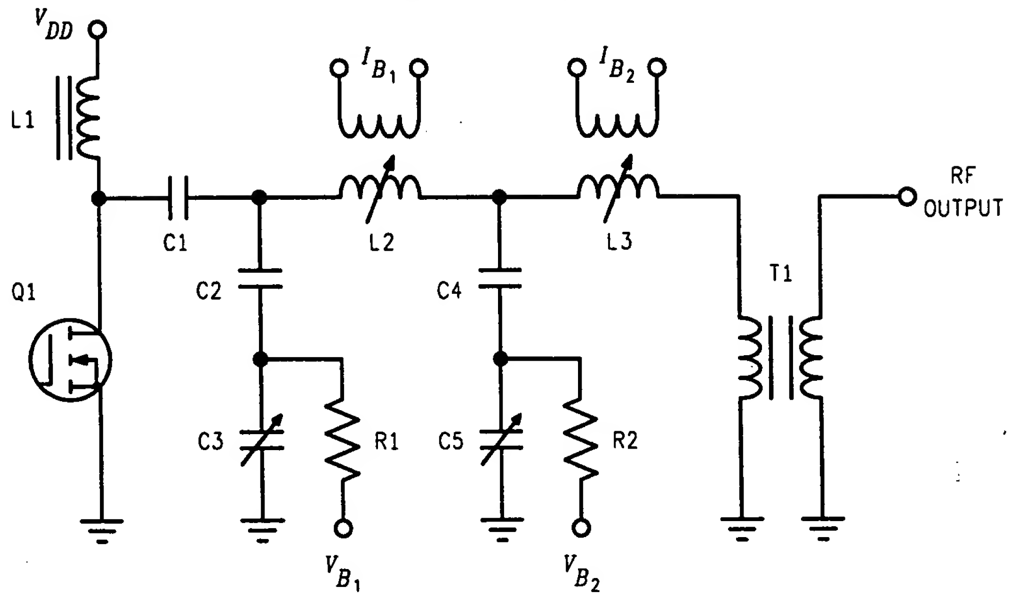

Figure 1. Electronically tuned class-E power amplifier.